Mission to Pluto:
A Navigation Assessment

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The navigation feasibility of directing a lightweight flyby/probe package to Pluto is discussed.

INTRODUCTION

A proposed NASA/JPL mission to Pluto, known until recently as Pluto Fast Flyby but now tentatively called Pluto Express, will send a pair of technologically innovative spacecraft to the Pluto-Charon system in the year 2009. Each of these spacecraft (spaced 6 months apart) will deliver a probe onto Pluto's surface and then briefly visit the planet via a flyby encounter. Since reaching the planet within reasonable time limits is desirable (no longer than 10 years), the spacecraft must be flung toward Pluto with high injection energies, resulting in heliocentric flyby velocities on the order of 16 km/second. Acquiring close-up science images at these high velocities will demand special orbit determination (OD) procedures.

High relative velocities and Pluto ephemeris uncertainties, combined with the insignificant mass of Pluto and the long round-trip light time, pose a singular challenge to navigation. The resolution presented here places greater reliance upon optical navigation than borne in previous missions, and includes a capability to process optical navigation data autonomously on board. The need for on board navigation is unequivocal if the mission is to achieve its goals.

The known characteristics of Pluto and its orbit are listed in Table 1.

Table 1
ORBITAL & PHYSICAL CONSTANTS OF PLUTO (EMO2000)

perihelion date	May 7, 1990
perihelion distance	29.69 au
eccentricity	0.247
inclination [0 ecliptic	17. l degrees
period	248 years
mean motion	1.46 degrees/year
solar distance at encounter (Jan. 9, 2009)	31.57 au
one-way light time at encounter (to Earth)	4 hours 3 I minutes
equatorial radius	l 150 km
mean density	~2 glee
GM	983 km^3/sec^2

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expected to be a narrow-field instrument with a pixel size of approximately 10 microradians. It will double as a navigation instrument.

Propulsion subsystem thrusters serve a dual purpose: trajectory maintenance and attitude control. A blowdown monopropellant hydrazine system performs trajectory maneuvers; attitude control employs cold gas press urant from the monopropellant tank. This tank is loaded with 24 kg of hydrazine, equivalent to approximately 330 m/s of velocity change[2]. This is an ample, probably excessive, margin. For as shown in the Maneuver Design sub-section, the 3 sigma mission delta-V requirement is much less than half this capability.

The probe, or drop ZOND, to be delivered onto Pluto's surface is a small (5.5 kg) Russian-provided *in situ* atmospheric-sampling and imaging package. ZOND and its accomodation mass will add 15 kg to the spacecraft. Thus the total wet mass at launch assumed for the mission is approximately 165 kg.

ZOND is powered by batteries with lifetimes of about one hour, so the probe will remain dormant during most of the mission. After release, and at a time preset by the spacecraft prior to release, ZOND will self-activate and begin broadcasting. In the current design, ZOND will precede the mothercraft to Pluto by 15 minutes, thereby restricting the maximum range between each to less than 50,000 km. Over this kind of distance, at a nominal rate of 20 kilobits/second, ZOND can transmit approximately 80 Megabits to the mothercraft during its one hour lifetime. Data will be transmitted over S-band frequencies (2.3 GHz) and received by a relay antenna on the mothercraft.

TRAJECTORY DESIGN

The mission follows a direct trajectory with launch of the first spacecraft on February 5, 2001 and arrival at Pluto roughly 7.9 years later, on January 9, 2009. This trajectory presumes launch on a Proton booster with a solid motor stack consisting of a Star 63, Star 37, and Star 27. The C3 injection energy is 250 km^2/sec^2.

Table 3 summarizes maneuver placements. The trajectory deflection maneuver at 25 days before closest approach deflects the spacecraft away from Pluto and slows it by 15 minutes, enabling ZOND to arrive first at Pluto.

Table 3
MANEUVER SCHEDULE

Maneuver	Rationale
TCM 1 Launch +45 days	correct injection errors
TCM2 Launch+ 120 days	correct injection errors
TCM3 Launch + I year	final targetting for remainder of cruise
TCM4 Pluto - 5 months	ZOND targetting (to Pluto)
TCM5 Pluto - 7 weeks	final ZOND targetting
TCM6 Pluto -25 days	trajectory deflection after ZOND release
ICM7 Pluto -7 days	final Pluto B-plane targeting

NAVIGATION DATA

This mission represents a departure from traditional tracking schedules for interplanetary spacecraft in that the mission must operate with a paucity of radiometric data during cruise from Earth to Pluto. Therefore, as discussed below, tracking schedules of 1 to 12 hours

Figure 1   Dispersions as a Function of Data Type and Data Density (10)

The navigation error model assumed in these analyses is described in the Appendix.

Table 5
BASELINE TRACKING SCHEDULE

Phase	Pass Duration
Launch	continuous from injection to launch+ 10 days
Cruise	two 4 hour passes per month
Maneuvers & probe release	one 6 hour pass per day from TCM-7 cloys to TCM+7 days & continuous from TCM - I hour to TCM+ I hour
Pluto Approach	continuous from Pluto-2 days to Pluto+4 hours

Optical Measurements

Optical navigation (OPNAV) data are necessary for successful navigation of the Pluto encounters. Optical images of Pluto and Charon against the star background taken on board the spacecraft will measure the spacecraft's Pluto-relative position to the level of accuracy required to deliver the probe to the planet's surface and target the main spacecraft to (he desired encounter geometry. Maneuvers designed to reach aimpoints in the Pluto B-plane will rely primarily on optical data since doppler data is insensitive to Pluto's mass.

The optical navigation campaign envisioned for this mission is divided into two phases. The first, or "far encounter", phase covers the period from 6 months to 3 days before closest approach. Activity during this phase will be similar to traditional OPNAV support for previous missions such as Voyager and Galileo. Ground-based image processing techniques will be applied to pictures transmitted to Earth from the spacecraft to extract the optical observable. These will be combined with the radiometric data using standard OD procedures.
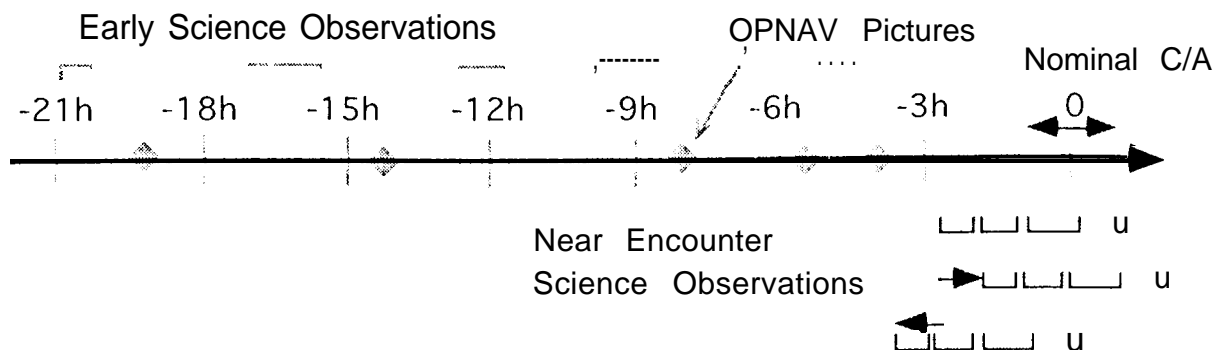
Figure 2   Operational Scenario for the Autonomous Optical Navigation System
Start times of near encounter science observations are adjusted based on solution for time of closest
approach from OPNAV pictures.

A prototype design for AONS has been completed recently[5,6]. The system has three primary components, or blocks. The functions of these blocks correspond to major steps in ground-based navigation procedures. An image processing block identifies the Pluto and star images in the current OPNAV picture and extracts their centers. The image centers are the navigation observable needed to solve the time of closest approach. The observable are then passed to an orbit determination block that computes an update to the time of closest approach. A geometry update block is included which executes before the other two blocks. This component uses the information from the previous solution to update the predicted spacecraft-Pluto geometry for the current picture. This information is then used to generate predicted Pluto and star image information for the image processing block. A fourth component of AONS applies the appropriate time shift to the start times of encounter science observations based on the solution from the orbit determination block.

The prototype system design for AONS emphasizes simplicity and exploits particular conditions of the flyby to reduce complexity, Since Pluto is expected to have a regular shape, simple edge detection techniques are applied to find the centers of the Pluto images in the image processing block. The "bootstrapping" introduced in the geometry update block limits the differences between predictions of Pluto image appearance and its actual appearance so that these simplified algorithms remain applicable. The nearly linear trajectory of the spacecraft relative to Pluto during the flyby leads to a substantial simplification in the orbit determination solution. The usual multi-parameter filter is reduced to a single cubic equation that gives the change in time of closest approach as a function of the difference between the actual and predicted Pluto image center locations.

The performance of the AONS prototype has been verified by implementation and testing in the Flight System Testbed (FST) at JPL. The FST provides a flight-like environment using both software tools and actual flight hardware to simulate spacecraft operation. Successful testing of AONS in the FST provides confidence that a flight-qualified version can be developed to meet a proposed requirement of less than 10 seconds uncertainty in the estimated time-to-go at 4 hours before closest approach. Of course, much work remains to be done before the system can be fully flight-qualified.

In summary, the optical navigation strategy for the Pluto encounter is exemplified by the data schedule shown in Table 6. The first 41 of the 53 total images in this schedule are

B-plane uncertainties for the last 70 clays are plotted in Figure 4. (Data schedules are also reproduced in the figure.) OPNAV information completely dominates the approach and leads to a 1 sigma B-plane error ellipse on the order of 50 km at 3 days before encounter -- the last opportunity to uplink a ground-based solution to the spacecraft. The corresponding uncertainty in the time-of-flight or downtrack direction at this time is much larger, on the order of 83 seconds or 1330 km. Doppler acquired at this time does not contribute in a meaningful way to the near encounter navigation but is valuable for reconstruction. (The rapid recovery of pre-maneuver OD after TCM6 anti TCM7 follows from reconstructions made possible by bracketing those maneuvers with one week's worth of doppler passes.)

Figure 4   Pluto Approach B-plane Uncertainties (1σ)

The time-of-flight uncertainty remains fixed at 83 or 84 seconds through-out the far encounter phase and well into the near encounter phase. This can be seen in Figure 5.

Figure 5 also indicates of the value of a ground-based ephemeris improvement program by comparing downtrack uncertainty between D] :200 and DE2008. The *difference* in downtrack error remains significant until the final clay (>6500 km).

A detailed view of the DE2008 plot in Figure 5 for the last 2 clays is supplied in Figure 6. This figure illustrates the unsatisfactory timing error still extant when the spacecraft is less than one day away from Pluto. Only when the geometry of Pluto with respect to the stellar background begins to change significantly can an estimate of time-to-go be calculated with precision. This begins about 18 hours before closest approach. At the time of the last OPNAV (-4 hours), the closest approach time will be known to within 8 seconds.

Post-flyby reconstruction will improve Pluto's heliocentric range tenfold to an accuracy of 12 km and potentially improve its mass estimate by two orders of magnitude.

ZOND. ZOND remains with the mothercraft until 30 days before closest approach, whereupon it is released. After the long cruise, however, two maneuvers will be necessary to target ZOND: TCM4 and TCM5. The last targeting maneuver, TCM5, is scheduled for November 15, 2008 (Pluto - 7 weeks). The arc for this latter maneuver contains 17 OPNAVS. As shown in Figure 7, the requirement of delivering ZOND to Pluto (*i.e.* impacting the planet) can be satisfied with this delivery. In the figure, impact uncertainties have been transformed into local coordinates.

Figure 7   ZOND Delivery Pluto impact Dispersions (1σ)

ZOND-release occurs one month after the TCM5 delivery, by which time 23 OPNAVS will have been acquired. The probe remains on a collision trajectory with Pluto while the mothercraft will deflect away. The additional 6 OPNAVs decreases uncertainty in latitude and longitude by about 40%, to 147 km and 115 km respectively. The corresponding time-of-flight uncertainty at release is 83 seconds. This can be compared, however, with a time-of-flight uncertainty equal to 16 minutes using DE200 (see Figure S).

The ZOND-relay link is limited to a 1σ time-of-flight uncertainty at ZOND-release of 210 seconds. Thus the DE2008 solution easily meets this requirement while DE200 exceeds it by a factor of 5.

'ZOND modeling differs in a minor way from the mothercraft model. The outstanding difference is a model for the probe-release mechanism. This device is assumed to introduce additional uncertainties into the initial state of the probe (see Appendix).

Maneuver Design

The first two maneuvers after launch are the largest in the mission. Their expected magnitudes are listed in Table 7. These magnitudes only pertain to initial corrections of the

introduction of (at least a partial) autonomous navigation capability represents a significant departure from previous mission operations and is among the first proposed use of such technology for a JPL interplanetary mission,

Anticipated ZOND delivery tolerances can be met by introducing a significantly improved ground-based Pluto ephemeris.

Maneuver analysis indicates that AV required for the mission is well within the capability of the spacecraft. Mean and 3σ AV estimates are 47 and 14 m/second respectively, giving a **216** m/second margin for the current tank size.

ACKNOWLEDGEMENT

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ZOND at Pluto: no opnaus, no ephemeris uncertainty
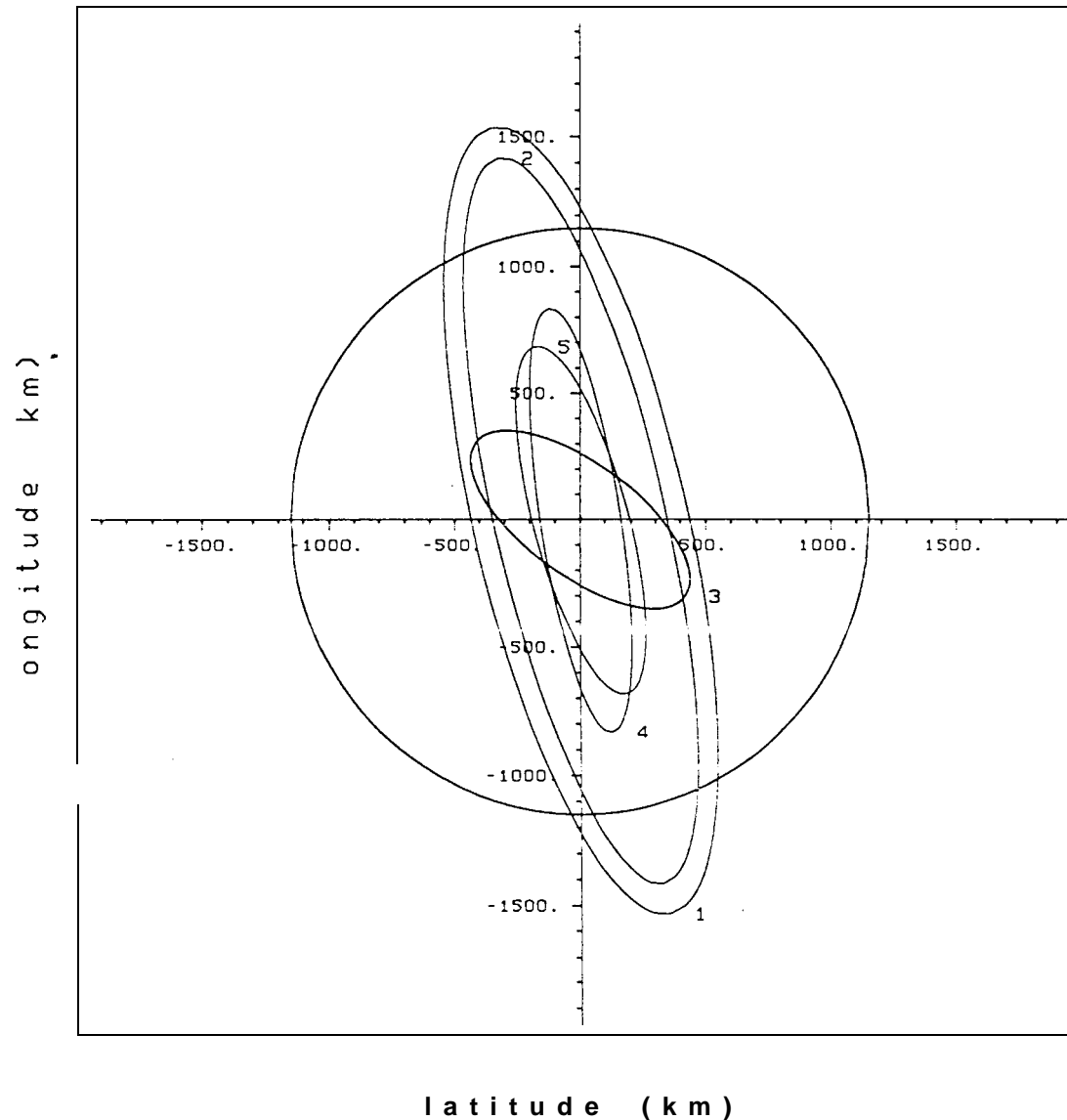
Legend

1 F2/F3(4 hr/mo)

2 F2/F3(4 hr/me), range (l/me)

3 F2/F3(4h/mo),range,DDor(1/mo)

4 F2/F3(8 hr/me), range

5 F2/F3(12 hr/me), range

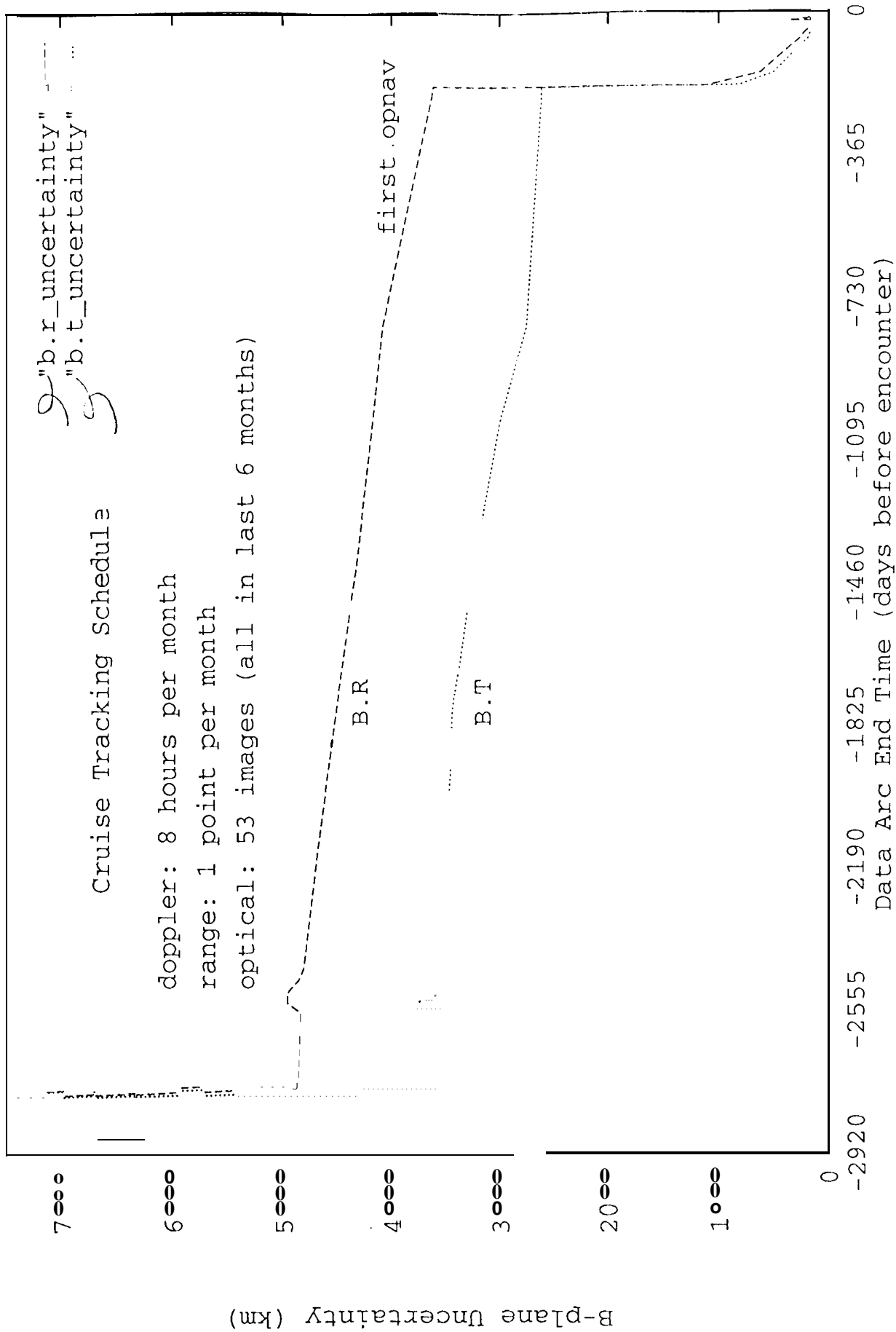Data cutoff: Pluto - 30 days

longitude (km).

latitude (km)

Origin
B.R Center =   .0
B.T Center z   .0

FIG 7 1

7.9 year duration

Cruise Tracking Schedule

doppler: 8 hours per month
range: 1 point per month
optical: 53 images (all in last 6 months)

"b.r_uncertainty"
"b.t_uncertainty"

first.opnav

B.R

B.T

B-plane Uncertainty (km)

encounter = Jan 9 20:24, 2009

Data Arc End Time (days before encounter)

Data Schedule and Approach Uncertainty

FIG X. 4

Ephemeris Comparison: DE200 vs. DE2008

FIG. 7 5

Downtrack Uncertainty (km)

Data Arc End Time (hours before encounter)

'48-46-44-42-40-38-36-34-32-30-28-26-24-22-20-18-16-14-12-10 -8 -6 -4 -2 0

1400
1200
1000
800
600
400
200
0

sec
75
0
5
25

"dtclose.unc"
"opnav.48hr"

autonomous opnav shutterings

FIG 9A

Legend

F2/F3 8 hr/mo),range,17opnavs

Data cuto : P uto - 60 days

R Center = Or g c   O
T Center =   O

latitude ·km)

longitude (km)

FIG. 87